Gamma-rays from pulsar wind nebulae in starburst galaxies

Karl Mannheim, Dominik Elsässer, and Omar Tibolla

Universitt Würzburg

Institut für Theoretische Physik und Astrophysik, Campus Hubland Nord, Emil-Fischer-Str. 31, D-97084 Würzburg, Germany Corresponding author: Karl Mannheim (mannheim@astro.uni-wuerzburg.de)

△ Abstract

Recently, gamma-ray emission at TeV energies has been detected from the starburst galaxies NGC253 (Acero et al., 2009) [1] and M82 (Acciari et al., 2009 [2]. It has been claimed that pion production due to cosmic rays accelerated in supernova remnants interacting with the interstellar gas is responsible for the observed gamma rays. Here, we show that the gamma-ray pulsar wind nebulae left behind by the supernovae contribute to the TeV luminosity in a major way. A single pulsar wind nebula produces about ten times the total luminosity of the Sun at energies above 1 TeV during a lifetime of 10^5 years. A large number of 3×10^4 pulsar wind nebulae expected in a typical starburst galaxy at a distance of 4 Mpc can readily produce the observed TeV gamma rays.

Recently, gamma-ray emission at TeV energies has been detected and M82 (Acciari et al., 2009 [2]. It has been claimed that pion interacting with the interstellar gas is responsible for the observed nebulae left behind by the supernovae contribute to the TeV lumiten times the total luminosity of the Sun at energies above 1 TeV wind nebulae expected in a typical starburst galaxy at a distance *Keywords:* gamma rays*, pulsar wind nebulae, starburst galaxies

1. Introduction

Supernova ejecta plowing through the interstellar gas form shock waves which have long been suspected as being responsible for the acceleration of cosmic rays [1-3]. The energetic cosmic ray particles traveling through the interstellar medium in a random walk can tap the shock wave energy by repeated scatterings on both sides of the shock in the diffusive-shock acceleration process. This has prompted the interpretation that the observed gamma rays are due to cosmic rays interacting with local interstellar gas and radiation [4]. However, a closer look at our Milky Way galaxy shows the importance of sources of a different origin for the total gamma ray luminosity at very high energies, and this poses the question of their contribution to the observed gamma ray emission from starburst galaxies.

A scan of the inner Galaxy performed with the H.E.S.S. array at TeV energies [5] revealed the striking dominance of pulsar wind nebulae (PWNe), although some faint diffuse emission could also be detected. Studies of the total (i.e. due to sources and diffuse) gamma ray emission from the Galaxy with Fermi-LAT show a flattening above 10 GeV energies due to the

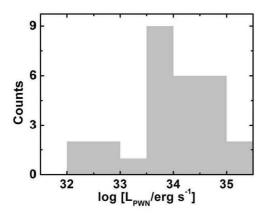
Fermi-LAT show a flattening above 10 GeV energies due to the increasing contribution from unresolved sources with rather hard spectra [6]. Late-phase PWNe show weak X-ray emission but bright TeV emission up to ages of 10⁵ years, as determined from the spin-down power of the pulsars [7]. The X-ray emitting electrons have shorter lifetimes than the electrons producing the TeV gamma rays by inverse-Compton scattering. The gamma-ray lifetime is finally terminated by adiabatic losses, breakup and diffusion into the interstellar medium [8]. This ancient PWN paradigm provides the most elegant solution of the riddle of TeV sources lacking X-ray counterparts such as HESS J1507-622, HESS J1427-608 and HESS J1708-410. A PWN toy model has been shown to explain the salient observational features of the off-plane source HESS J1507-622 [9]. Many unidentified sources have already been identified as PWNe after their discovery (such as HESS J1857+026 or HESS J1303-631); many other unidentified sources are considered to be very likely PWNe (such as HESS J1702-420); and also in sources that have several plausible counterparts, the PWNe contribution cannot be avoided (such as hot spot B in HESS J1745-303 or HESS J1841-055).

In the following, we compare the gamma-ray luminosities associated with PWNe and cosmic rays, respectively, in starforming galaxies.

2. PWN luminosity at TeV energies

Prior to the Fermi era, a total of 60 galactic PWNe were known in X-rays and TeV gamma rays; according to [10] 33 of them have measured TeV fluxes. Future observations will have to confirm some of the more controversial identifications reported in [10]. Significant progress for a number of sources has recently been achieved by the MILAGRO, VERITAS, MAGIC, and HESS collaborations and is ongoing. Moreover, new TeV PWNe surrounding known pulsars have been discovered [11]. Fermi is now probing deeper into the population of galactic sources at GeV energies, confirming pulsars in some of the suspected PWN. In those cases where the pulsar is not found, it could already have spun down or emit preferentially into a solid angle off the line of sight, still in line with a PWN association. The properties of the subsample of 28 PWNe from [10] which are younger than

$$t_{\text{cool}}(1 \text{ TeV}) = 1.3 \times 10^5 (\text{B}/10 \,\mu\text{G})^{-2} \text{ years}$$
 (1)



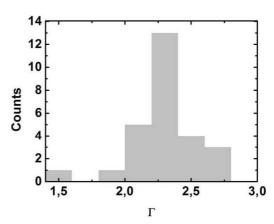


Figure 1: Distribution of (1-10) TeV luminosities and photon indices of 28 PWN with TeV detections and spin-down ages less than 10⁵ years from the sample compiled in ref. [10]. Note that the photon index does not correlate with luminosity.

have been considered here as representative for the putative PWNe population in starburst galaxies. Their average luminosity is given by $\bar{L}=2.75\times 10^{34}~\rm erg~s^{-1}$ and their average differential photon index by $\Gamma=2.3~(dN/dE\propto E^{-\Gamma})$ as shown in Fig. 1. If the decrease of the counts at low luminosities is due to the limited flux sensitivity of the TeV observations, \bar{L} would be overestimated only within factors of order unity for reasonable assumptions. Observationally, only pulsars with a spin-down power of $\dot{E}_c>4\times 10^{36}~\rm erg~s^{-1}$ develop detectable PWNs [12]. The spin-down power *at birth* is higher than \dot{E}_c for canonical rotation energies of $10^{49}~\rm erg~[13]$. The high PWN luminosities are a natural consequence of this scenario.

The dominance of the PWN population on the TeV sky relates to the fact that they show hard spectra and long TeV life-times compared with shell-type supernova remnants. As long as the pulsar winds remain enclosed by the preceding supernova bubble, their properties will be largely independent on the interstellar medium. For high kick velocities, the PWN evolution into the interstellar medium in starburst galaxies with their higher density and stronger magnetic field might be somewhat altered, but we ignore this aspect here and leave the details of this problem to future work and further observational constraints.

The number of PWN can be coarsely estimated from the core-collapse supernova rate. Measurements of 26 Al in the MeV range are consistent with a supernova rate of R = 0.02 per year in the Milky Way galaxy assuming a Kroupa-Scalo initial mass function [14]. The maximum number of TeV-emitting PWN in the Milky Way galaxy is given by

$$N_{\text{PWN}} = 2.6 \times 10^3 \left(R/0.02 \text{ year}^{-1} \right)$$
 (2)

if we neglect other final states that do not develop a PWN such as black holes or low-magnetic field neutron stars. Some neutron stars might produce the PWN with a delay given by the rise time of the magnetic field that was initially submerged under the neutron star surface. The corresponding number of shell-type supernova remnants, assuming a life-time of 10^4 years for them, is given by $N_{\rm SNR}=200$, and this compares to the number of eight SNR which have been detected at TeV

energies. If the same discovery fraction of 1: 25 is applied to the PWN, ignoring the somewhat different observational biases for the two types of sources for the sake of simplicity, we expect a number of 100, which is actually close to the number of known TeV-emitting PWN plus the unidentified TeV sources. Although these estimates must be treated with extreme caution, they show that the scenario is at least plausible.

Estimating the PWN luminosity of starburst galaxies is now straightforward. Since the starburst ages are typically of the order of $10^6 - 10^7$ years [15] and thus much longer than the cooling time of the TeV electrons, the number of PWN contributing to the TeV luminosity can be obtained from the current supernova rate (assuming steady-state activity). Multiplying the rate with the cooling age, the luminosity \bar{L} per PWN, and the differential spectrum with $\Gamma = 2.3$, the total luminosity above 1 TeV is given by

$$L_{\text{PWN}} (> E) = 7 \times 10^{38} \left(\frac{R}{0.2 \text{ /year}} \right) \left(\frac{E}{1 \text{ TeV}} \right)^{-0.3} \text{erg s}^{-1} (3)$$

As shown in Fig. 2, the TeV luminosities evaluated for the starburst galaxies with the above formula are in fair agreement with the observed values. At lower energies ($E < 1~{\rm TeV}$), the spectral index changes by $\Delta\Gamma = -0.5$ at the cooling break, and this effect can be seen in the synchrotron radiation component [16]. The transition from the harder to the softer spectrum will be rather broad for a realistic distribution of magnetic field strengths. Since the observed gamma-ray spectra of the starburst galaxies require a continuation of the spectrum with $\Gamma \approx 2.3$ towards lower energies, additional sources such as cosmic rays seem to be required to explain their GeV luminosities.

3. Comparison with cosmic-ray induced gamma ray emission

The total cosmic ray luminosity from shell-powered supernova remnants is given by

$$L_{\rm CR} = 6 \times 10^{41} \left(\frac{R}{0.2 \text{ year}^{-1}} \right) \left(\frac{E_{\rm SNR}}{10^{51} \text{ erg}} \right) \left(\frac{\varepsilon}{0.1} \right) \text{ erg s}^{-1}$$
 (4)

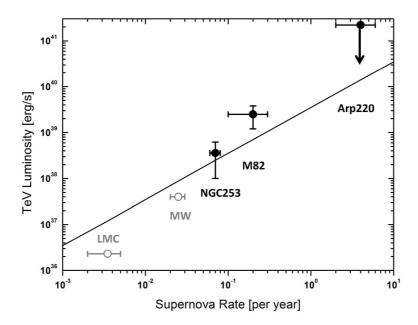


Figure 2: Comparison of the PWN luminosities at (1-10) TeV expected from Eq.(3) (solid line) with the observed luminosities (data points). The error bars of the filled circles reflect the uncertainties of the supernova rates [12,17-23] and of the observed TeV luminosities [1,2,24], accounting for distance and flux uncertainties. Redshift-independent distance measurements were retrieved from the NED (nedwww.ipac.caltech.edu). The grey open circles denote the estimated TeV luminosities of the Milky Way galaxy and the Large Magellanic Cloud (dominated by 30 Doradus), respectively by extrapolating from Fermi measurements with a power law of index -2.3 above 10 GeV [6,25].

where $E_{\rm SNR}$ denotes the kinetic energy and ε the acceleration efficiency. If the cosmic rays are efficiently stored, they loose their energy by inelastic interactions with the interstellar medium, and the calorimetric gamma ray (and neutrino) luminosity becomes a significant fraction of the luminosity Eq.(4) [26,27]. In fact, cosmic ray heating of the dense starforming clouds in starburst galaxies has been directly observed [28], and the observed gamma ray spectra at GeV energies are indeed quite flat. In the absence of other loss processes, the fraction of the cosmic ray luminosity that ends up in GeV gamma rays energies can been determined numerically to be ~ 0.25 [29], and so we expect $L_{\rm CR,\gamma}({\rm GeV}) \simeq 1.5 \times$ $10^{41} (R/0.2 \text{year}^{-1}) (\varepsilon/0.1) \text{ erg s}^{-1}$ in the calorimetric limit. With the mean distances from the NED 3.8 Mpc for M82 and 3.1 Mpc for NGC253 the observed luminosities are $L_{\gamma,M82}$ (GeV) = $2.2 \times 10^{40} \text{ erg s}^{-1} \text{ and } L_{\gamma, \text{NGC}253}(\text{GeV}) = 5.6 \times 10^{39} \text{ erg s}^{-1}, \text{ im-}$ plying an efficiency of $\varepsilon \simeq 0.01$ for $R_{\rm M82} = 0.25~{\rm year}^{-1}$ and $R_{\text{NGC253}} = 0.07 \text{ year}^{-1}$ (see caption of Fig.2 for references). The values are lower than the values of $\varepsilon \simeq 0.1$ in the Ginzburg-Syrovatskii scenario for the origin of cosmic rays in the Milky Way galaxy [3], perhaps due to adiabatic losses in the overpressured starburst region or the hotter interstellar medium compared to the Milky Way.

Pion production energy losses further compete with advection and diffusion. Since the diffusive escape time $t_{\rm diff}$ decreases with increasing energy, there is an energy $E_{\rm diff}$ at which the pion production time scale $t_{\pi} = 2.5 \times 10^5 (n/200 \, {\rm cm}^{-3})^{-1}$ years scaled

with the mean density of the interstellar gas n becomes larger than $t_{\rm diff}$. The gamma ray luminosity in the optically thin range, i.e. at $E > E_{\rm diff}$, is given by

$$L_{\text{CR},\gamma}(E) = \frac{L_{\text{CR}}t_{\text{diff}}(E)}{t_{\pi}}$$
 (5)

In the Milky Way Galaxy, $t_{\rm diff}$ can be determined from the ¹⁰Be/⁹Be isotope ratio in cosmic rays, showing the energy dependence $t_{\rm diff} \propto E^{-0.5}$ above 1 GeV. Since the energy dependence results from universal properties of turbulent transport, we can assume the same energy dependence for the escape time in starburst galaxies. A similar energy dependence in starburst galaxies would mean that the cosmic ray particles must diffuse out of the high-density star forming region and enter the lowdensity wind zone at sufficiently high energies. Here, advective transport becomes dominant which further reduces the efficiency of the cosmic rays to produce TeV gamma rays. The diffusion coefficient inferred from radio measurements of starburst galaxies in the wind zone has a value of $D = 2 \times 10^{29} \text{ cm}^2 \text{ s}^{-1}$ at GeV energies [30], and even larger values might be appropriate for a hot, turbulent, and highly magnetized star-forming region. The transition from diffusive to advective propagation occurs at a scale height [31] of

$$z = 650 \frac{D/2 \times 10^{29} \text{ cm}^2 \text{ s}^{-1}}{\text{v}/1000 \text{ km s}^{-1}} \text{ pc}$$
 (6)

considering that the wind speed reaches $\sim 1000 \, \text{km s}^{-1}$ [32-34]. The corresponding conservative estimate of the diffusive escape

time at GeV energies is thus given by

$$t_{\text{diff}} = 6 \times 10^5 \frac{(z/650 \text{ pc})^2}{D/2 \times 10^{29} \text{ cm}^2 \text{ s}^{-1}} \left(\frac{E}{\text{GeV}}\right)^{-0.5} \text{ years.}$$
 (7)

The diffusion time scale becomes shorter than t_{π} above $E_{\rm diff} \approx 10\,$ GeV. The steady-state spectrum due to cosmic ray interactions displays the energy dependence of the injection spectrum $\Gamma_{\rm i} = 2.2\,$ for $E < 10\,$ GeV

$$L_{\text{CR},\gamma}(E) = 1.5 \times 10^{41} \left(\frac{R}{0.2 \text{ year}^{-1}}\right) \left(\frac{\epsilon}{0.1}\right) \left(\frac{E}{1 \text{ GeV}}\right)^{-0.2} \text{ erg s}^{-1}$$
 (8)

Above $E_{\rm diff} \approx 10$ GeV, the spectrum steepens according to Eq.(5)

$$L_{\text{CR},\gamma}(E) = 9 \times 10^{40} \left(\frac{R}{0.2 \text{ year}^{-1}}\right) \left(\frac{\epsilon}{0.1}\right) \left(\frac{E}{10 \text{ GeV}}\right)^{-2.7} \text{ erg s}^{-1}$$
 (9)

Due to this steepening, the PWNe with their flatter spectrum $\bar{\Gamma}=2.3$ come into play towards higher energies. Combining Eq.(3) and Eq.(8) and adopting $\varepsilon=0.01$ we obtain

$$\begin{split} \Gamma(\text{GeV} - \text{TeV}) = \\ 2 + \frac{1}{3} \left(\log \left[L_{\text{CR}, \gamma}(\text{GeV}) \right] - \log \left[L_{\text{PWN}}(\text{TeV}) \right] \right) &\simeq 2.4 \ (10) \end{split}$$

in fair agreement with the observations given the crude assumptions. The agreement becomes somewhat better by including the cosmic ray component from Eq.(9) at TeV energies. The result is robust, i.e. independent of the supernova rate. Currently, the observations are too sparse at 10 GeV to 1 TeV to show the shallow dip that might emerge due to the steepening of the cosmic-ray induced component and the onset of the PWN component.

4. Discussion and conclusions

Starburst galaxies such as M82 and NGC253 show a much harder GeV gamma-ray spectrum than the Milky Way galaxy, and this is in line with the high gas density in the star forming regions and a cosmic-ray origin of the gamma rays. However, diffusive-advective escape of the cosmic rays from the star-forming regions should lead to a steepening of the cosmic-ray induced gamma-ray spectrum above ≈ 10 GeV, in which case the cosmic rays would fall short in explaining the high TeV luminosities. The effects of the escaping cosmic rays can be seen on larger scales in the radio emission associated with the fast superwinds. The PWNe associated with core-collapse supernovae in star-forming regions can readily explain the observed high TeV luminosities. Since the injection spectrum of cosmic rays, which determines the slope of the observed spectrum between 100 MeV and 10 GeV, has the slope $\Gamma = 2.2 - 2.3$ and the PWN also have a spectrum with $\Gamma = 2.3$ above ≈ 100 GeV, the total spectrum from GeV to TeV shows little change across a wide band. Measurements of the TeV luminosities of galaxies such as LMC or Arp220 will be important to better understand the relative contributions of the gamma-ray emitting components in starburst galaxies.

Acknowledgements

We are indepted to the memory of Okkie de Jager who encouraged us to put forward this research paper. O.T. acknowledges support by the BMBF under contract 05A08WW1.

References

- [1] Acero, F., et al. (H.E.S.S.) Detection of Gamma Rays from a Starburst Galaxy, Science 326, 1080-1082 (2009)
- [2] Acciari, V.A., et al. (VERITAS) A connection between star formation activity and cosmic rays in the starburst galaxy M82, Nature 462, 770-772 (2009)
- [3] Ginzburg, V. L. & Syrovatskii, S. I. The Origin of Cosmic Rays, New York: Macmillan (1964)
- [4] Persic, M., Rephaeli, Y., Arieli, Y. Very-high-energy emission from M82, Astron. & Astrophys. 486, 143-149 (2008)
- [5] Aharonian et al. (H.E.S.S.) A New Population of Very High Energy Gamma-Ray Sources in the Milky Way Science 307,1938-1942 (2005)
- [6] Strong, A., et al. (Fermi): Fermi Symposium Contributions of source populations to the Galactic diffuse emission, P4-139, 2-5 Nov. 2009, Washington, USA (2009)
- [7] Mattana, F., Falanga, M., Gtz, D., Terrier, R., Esposito, P., Pellizzoni, A., De Luca, A., Marandon, V., Goldwurm, A., and Caraveo, P. A. *The Evolution of the - and X-Ray Luminosities of Pulsar Wind Nebulae*, Astrophys. J. 694, 12-17 (2009)
- [8] de Jager, O. C., et al. Unidentified Gamma-Ray Sources as Ancient Pulsar Wind Nebulae, 31st International Cosmic Ray Conference, 31st ICRC, Lodz, Poland, 2009 (astro-ph/0906.2644)
- [9] Acero et al. Discovery and follow-up studies of the extended, off-plane, VHE gamma-ray source HESS J1507-622, Astron. & Astrophys. 525,45 (2011)
- [10] Kargaltsev, O., Pavlov, G. Pulsar Wind Nebulae in X-rays and TeV gamma-rays, in: Procc of "X-ray Astronomy 2009" conference, Bologna, Italy, September, 2009 published by AIP (astro-ph/1002.0885)
- [11] Abramowski et al. Detection of very-high-energy gamma-ray emission from the vicinity of PSRB170644 and G343.12.3 with H.E.S.S., 2011, Astron. & Astrophys., in press (astro-ph/1102.0773)
- [12] Gotthelf, E.V. A Spin-down Power Threshold for Pulsar Wind Nebula Generation?, in: Proc. of "Young Neutron Stars and Their Environments", IAU Symposium 218, eds. F. Camilo and B.M. Gaensler, pp. 225 228, San Francisco: Astron. Soc. Pac. (2004)
- [13] Gaensler, B.M., Slane, P.O. The Evolution and Structure of PulsarWind Nebulae, Annu. Rev. Astro. Astrophys. 44, 17-47 (2006)
- [14] Diehl, R. et al. (INTEGRAL) Radioactive 26Al from massive stars in the Galaxy, Nature 439, 45-47 (2006)
- [15] Thornley, M.D., et al. Massive Star Formation and Evolution in Starburst Galaxies: Mid-infrared Spectroscopy with the ISO Short Wavelength Spectrometer, Astrophys. J. 539, 641-657 (2000)
- [16] de Jager, O. et al. Estimating the Birth Period of Pulsars through GLAST LAT Observations of Their Wind Nebulae, Astrophys. J. Lett. 678, L113-L116 (2008)
- [17] Colina, L., Perez-Olea, D. On the origin of the radio emission in IRAS galaxies with high and ultrahigh luminosity - The starburst-AGN controversy MNRAS 259, 709-724 (1992)
- [18] van Buren, D., & Greenhouse, M. A. A more direct measure of supernova rates in starburst galaxies, Astrophys. J. 431, 640-644 (1994)
- [19] Paglione, T. et al. Diffuse Gamma-Ray Emission from the Starburst Galaxy NGC 253, Astrophys. J. 460, 295-302 (1996)
- [20] Ulvestad, J. & Antonucci, R. VLA Observations of NGC 253: Supernova Remnants and H II Regions at 1 Parsec Resolution Astrophys. J. 488, 621 (1997)
- [21] Huang, Z. P., Thuan, T. X., Chevalier, R. A., Condon, J. J., Yin, Q. F. Compact radio sources in the starburst galaxy M82 and the Sigma-D relation for supernova remnants, Astrophys. J. 424, 114-125 (1994)
- [22] Kronberg, P. P., Biermann, P., Schwab, F. R. The nucleus of M82 at radio and X-ray bands - Discovery of a new radio population of supernova candidates, Astrophys. J. 291, 693-707 (1985)
- [23] Lonsdale, C. J. et al. VLBI Images of 49 Radio Supernovae in Arp 220, Astrophys. J. 647, 185-193 (2006)

- [24] Albert, J. et al. (MAGIC) First Bounds on the Very High Energy -Ray Emission from Arp 220, Astrophys. J. 658, 245-248 (2007)
- [25] Abdo, A.A., et al. (Fermi Collaboration), Observations of the Large Magellanic Cloud with Fermi Astron. & Astrophys. 512, A7 (2010)
- [26] de Cea del Pozo, E., Torres, D.F., Rodrguez, A.Y. Model analysis of the very high Energy detections of the starburst galaxies M82 and NGC253, Fermi Symposium, Washington, D.C., Nov. 2-5 (2009)
- [27] Abdo, A.A., et al. (Fermi) Detection of Gamma-Ray Emission from the Starburst Galaxies M82 and NGC 253 with the Large Area Telescope on Fermi, Astrophys. J. 709, L152-L157 (2010)
- [28] Bradford, C.M., Nikola, T., Stacey, G.J., Bolatto, A.D., Jackson, J.M., Savage, M.L., Davidson, J.A., Higdon, S.J. CO (J=76) Observations of NGC253: Cosmic-ray-heated Warm Molecular Gas Astrophys. J. 586, 891-901 (2003)
- [29] Lacki, B.C., et al., Astrophys. J. 734, 107 (2010)
- [30] Heesen, V., Beck, R., Krause, M., Dettmar, R.-J. Cosmic rays and the magnetic field in the nearby starburst galaxy NGC 253. I. The distribution and transport of cosmic rays, Astron. & Astrophys. 494, 563-577 (2009)
- [31] Breitschwerdt, D., Dogiel, V. A., and Völk, H. J. The gradient of diffuse gamma-ray emission in the Galaxy, Astron. and Astrophys. 385, 216-238 (2002)
- [32] Westmoquette, M.S., Gallagher, J.S., Smith, L.J., Trancho, G., Bastian, N., and Konstantopoulos, I.S. The optical structure of the starburst galaxy M82. II. Nebular properties of the disk and inner-wind, Astrophys. J. 706, 1571-1587 (2009)
- [33] Bauer, M., Pietsch, W., Trinchieri, G., Breitschwerdt, D., Ehle, M., Freyberg, M. J., Read, A. M. XMM-Newton observations of the diffuse X-ray emission in the starburst galaxy NGC 253, Astron. and Astrophys. 489, 1029-1046 (2008)
- [34] Strickland, D.K. & Heckman, T.M. Supernova Feedback Efficiency and Mass Loading in the Starburst and Galactic Superwind Exemplar M82, Astrophys. J. 697, 2030-2056 (2009)